

A testable hidden-sector model for Dark Matter and neutrino masses

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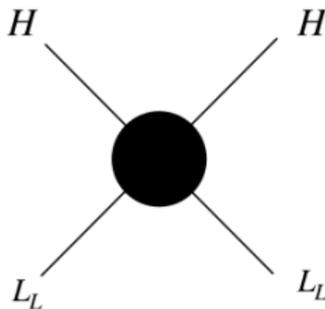
- ▶ Experimentally observed non-vanishing **neutrino masses**



Open questions of the SM

- ▶ Experimentally observed non-vanishing **neutrino masses**

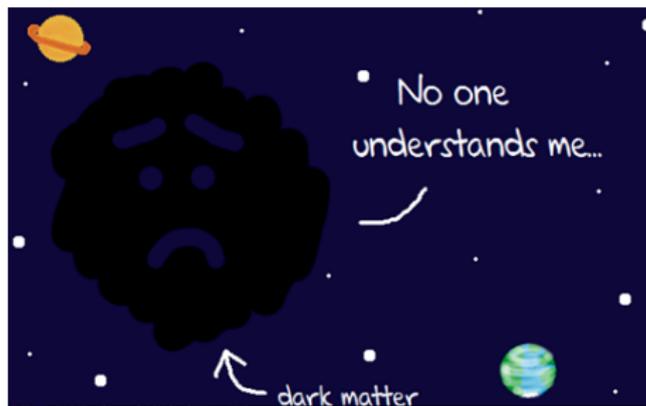
to introduce a mass term for neutrinos we need to add new particles to the SM



→ strong evidence for an extended particle content and BSM physics
however no signal of these particles yet

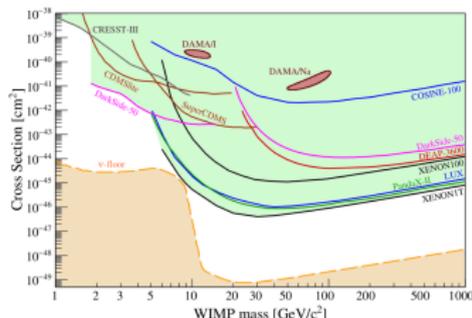
Open questions of the SM

- ▶ Experimentally observed non-vanishing **neutrino masses**
- ▶ Need for a **Dark Matter** candidate



Dark Matter

- ▶ Need for a **Dark Matter** candidate
- ▶ large experimental effort to detect DM
[Schumann '19]
- ▶ so far DM only observed via its gravitational interactions
- ▶ we have not seen particle nature of DM
→ if DM is a particle it interacts only very weakly with matter

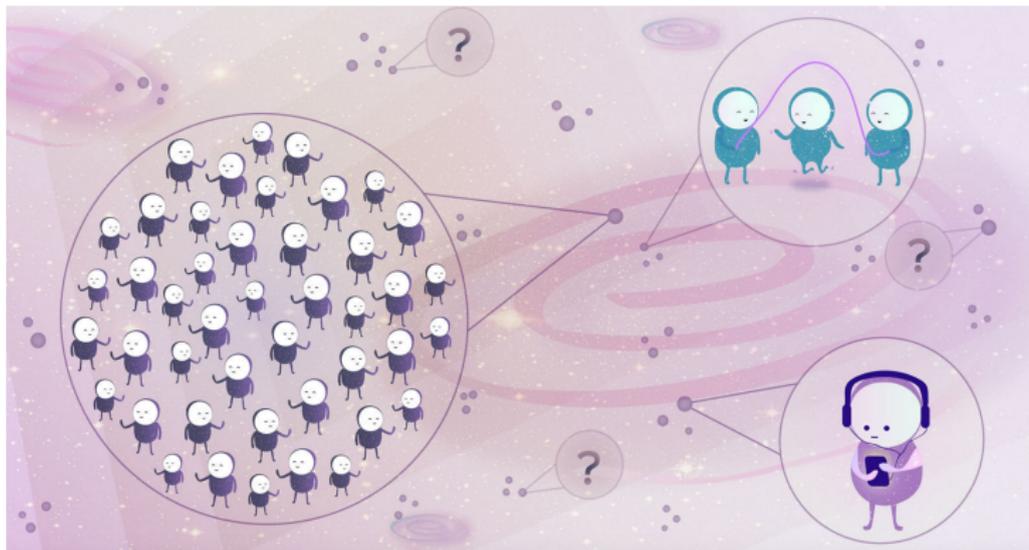


Open questions of the SM

- ▶ Experimentally observed non-vanishing **neutrino masses**
- ▶ Need for a **Dark Matter** candidate
- ▶ measured fermion masses and mixings are very different: **flavour puzzle**
- ▶ CP violating term in QCD is very small: **strong CP** problem
- ▶ Higgs boson found but it is very light: **hierarchy problem**

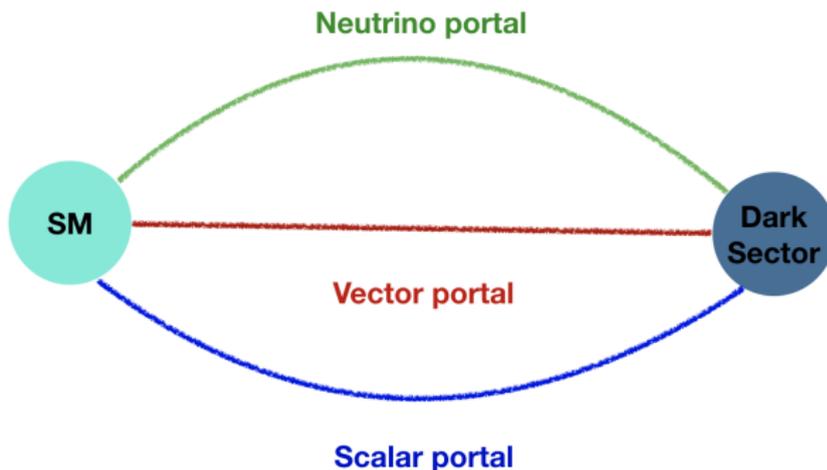
non-observation of new physics might imply that the new physics sector interacts only very weakly with visible sector & particles not directly charged under SM group

does not exclude that the new sector has a **rich structure** itself & mass scales possibly well below the weak scale



Hidden sectors: Portals [Essig et al. 1311.0029]

$$\begin{array}{ll} \epsilon F^{\mu\nu} F'_{\mu\nu} & \text{vector portal} \\ \lambda H^2 S^2 + \mu H^2 S & \text{scalar portal} \\ y(\bar{L}\tilde{H})N & \text{neutrino portal} \end{array}$$



Hidden sector model for neutrino masses and DM

Based on *"A testable hidden-sector model for Dark Matter and neutrino masses"*

in collaboration with Mathias Pierre

published in JHEP **2002**, 068 (2020), arXiv: 1912.06661



- ▶ introduce dark $U(1)'$ under which the particle in the hidden sector are charged

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- ▶ introduce dark $U(1)'$ under which the particle in the hidden sector are charged
- ▶ hidden sector contains right-handed neutrinos which give mass to the SM neutrinos via an extended seesaw mechanism
- ▶ simplest anomaly-free version of the theory: additional chiral fermions need to be introduced
- ▶ find viable DM candidate, one massless state which contributes to the effective relativistic degrees-of-freedom in the early Universe

Hidden sector model for neutrino masses and DM [JG,

Pierre '19]

	$U(1)'$ breaking	ESS		DM candidate		massless f.
Field	Φ	N_R	N'_R	χ_R	χ_L	ω_L
$U(1)'$	1	0	1	5	4	4
Multiplicity	1	3	3	1	1	1

SM particles neutral under $U(1)'$

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$$\mathcal{L}_{\text{fermions}} = -y_\nu^\alpha \overline{L}_L^\alpha \widetilde{H} N_R - \frac{\mu_N}{2} \overline{N}_R^c N_R - y_N \Phi^* \overline{N}_R^c N'_R - y_\chi \Phi \overline{\chi}_R \chi_L + \text{h.c.}$$

DM and sterile neutrino mass have the **same** origin!

Hidden sector model for neutrino masses and DM [JG,

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fermion mass matrix ($\nu_L^c, N_R, N'_R, \chi_L^c, \chi_R$):

$$M = \left(\begin{array}{ccc|cc} 0 & y_\nu \tilde{H} & 0 & 0 & 0 \\ y_\nu^T \tilde{H}^\dagger & \mu_N & y_N \Phi & 0 & \\ 0 & y'_N \Phi^* & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & y_\chi \Phi^* \\ 0 & 0 & 0 & y_\chi^T \Phi & 0 \end{array} \right)$$

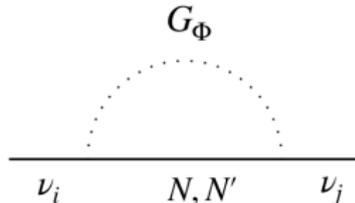
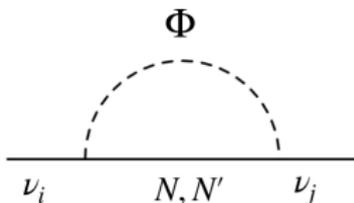
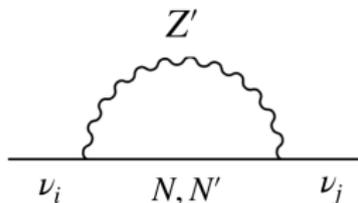
fermion mass matrix (ν_L^c, N_R, N'_R) :

$$M_\nu = \begin{pmatrix} 0 & y_\nu \tilde{H} & 0 \\ y_\nu^T \tilde{H}^\dagger & \mu_N & y_N \Phi \\ 0 & y'_N \Phi^* & 0 \end{pmatrix}$$

massless neutrinos at tree level!

→ **loop-level** generation of neutrino masses

loop-level generation of neutrino masses



$$M_R \ll m_{Z'}, m_\phi$$

$$M_R \gg m_{Z'}, m_\phi$$

$$m_3 = N_F \frac{g_{Z'}^2, m_D^2 \mu_N}{16\pi^2 M_R^2} \left(3 + \frac{m_\phi^2}{m_{Z'}^2} \right)$$

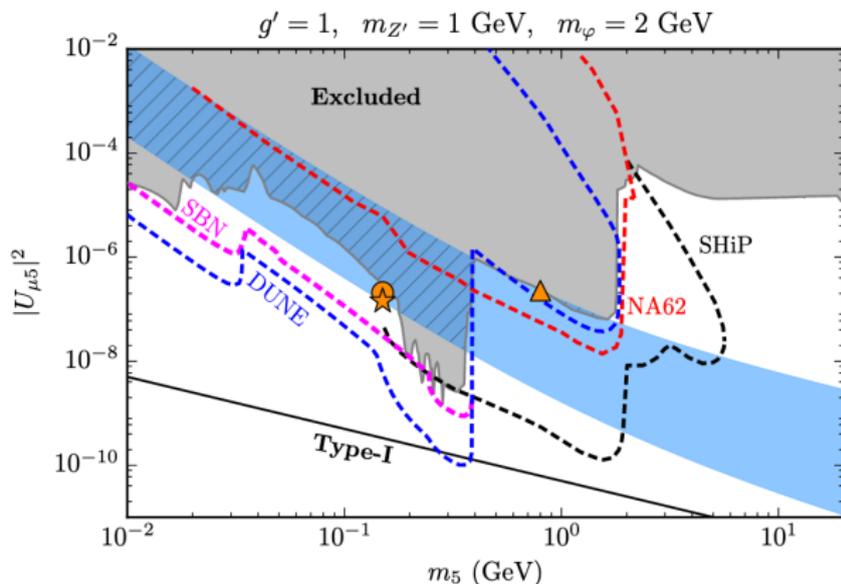
$$m_3 = N_F \frac{g_{Z'}^2, m_D^2 \mu_N}{16\pi^2 m_{Z'}^2} \left[3 \log \left(\frac{m_{Z'}^2}{M_R^2} \right) + \log \left(\frac{m_\phi^2}{M_R^2} \right) - 4 \right]$$

Neutrino phenomenology

same neutrino sector as in [Ballett, Hostert, Pascoli '19]

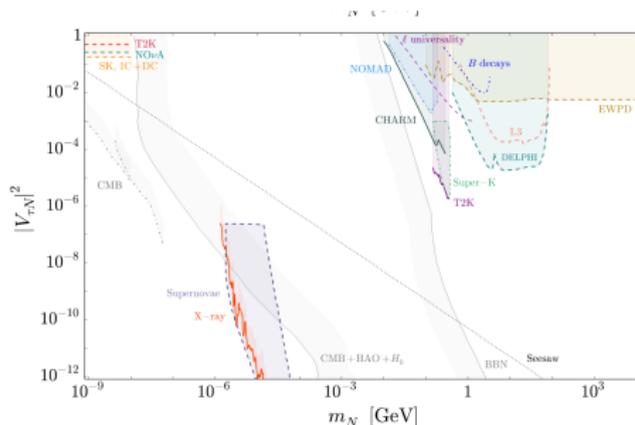
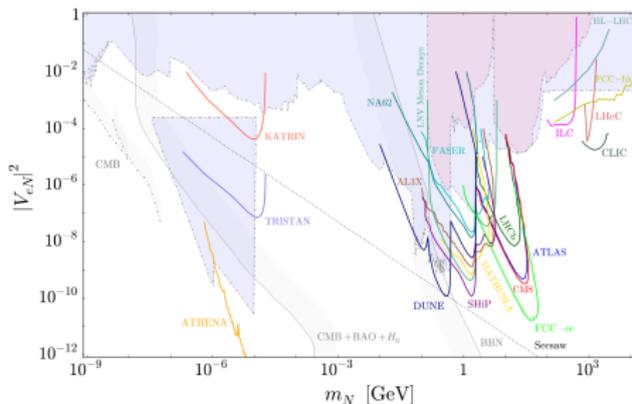
(see also [Bertuzzo, Jana, Machado, Zukanovich Funchal '18] for similar model)

active-sterile mixing angle: $U_{\alpha,i} = \frac{m_D}{\sqrt{2}M_R}$

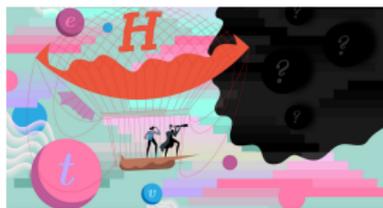


Neutrino phenomenology

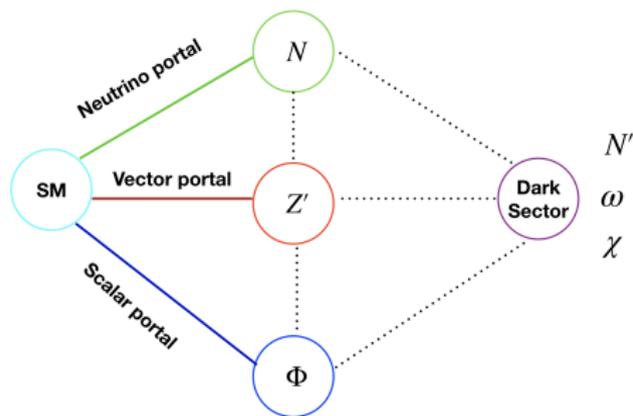
constraints on mixing with electron and tau neutrinos [Bolton, Deppisch, Dev '19]



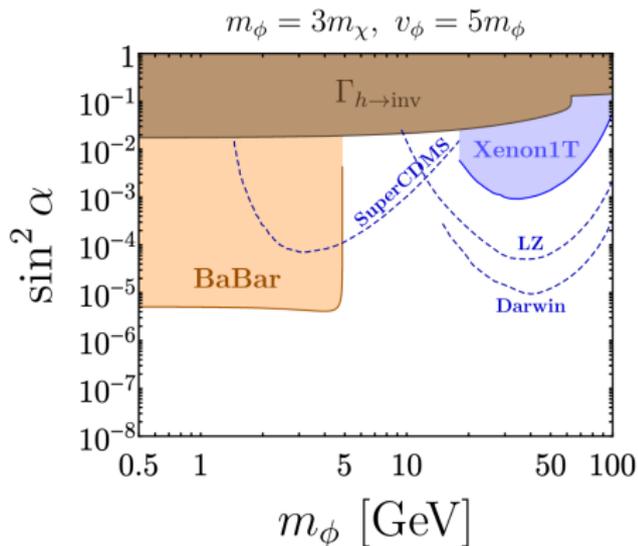
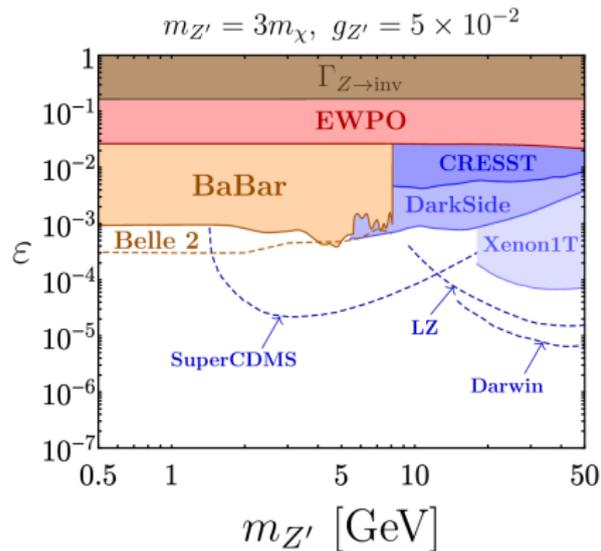
three portals to the SM



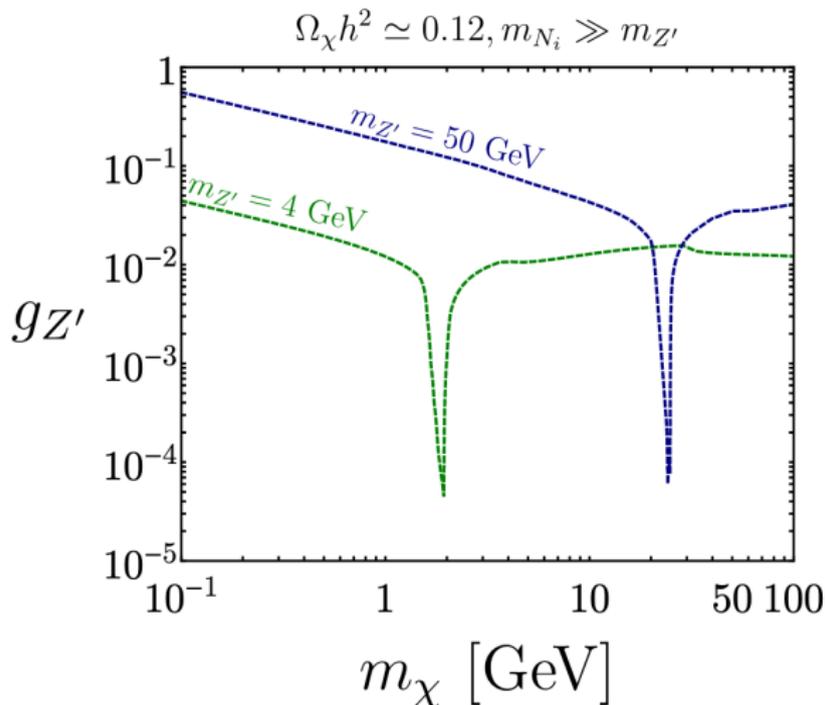
- ▶ Neutrino portal: active-sterile mixing
- ▶ Scalar portal: mixing with Higgs
- ▶ Vector portal: kinetic mixing



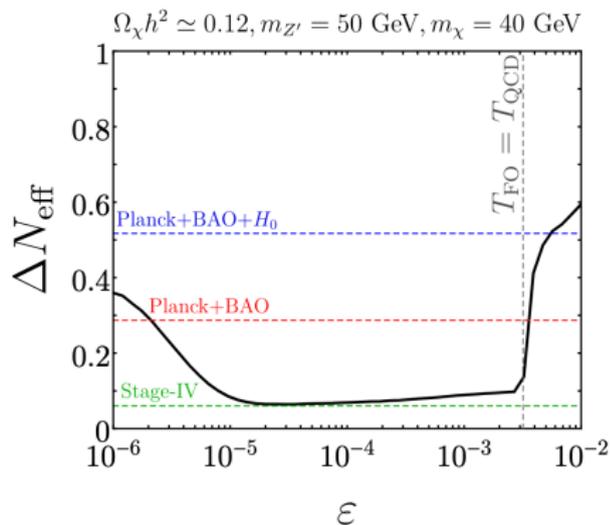
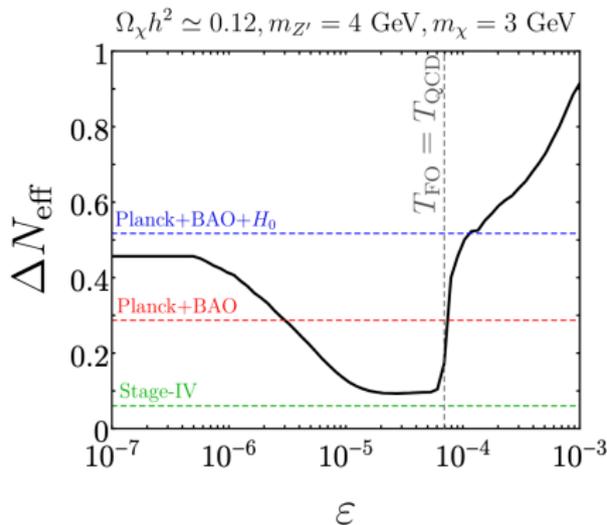
constraints on dark scalar and dark gauge boson

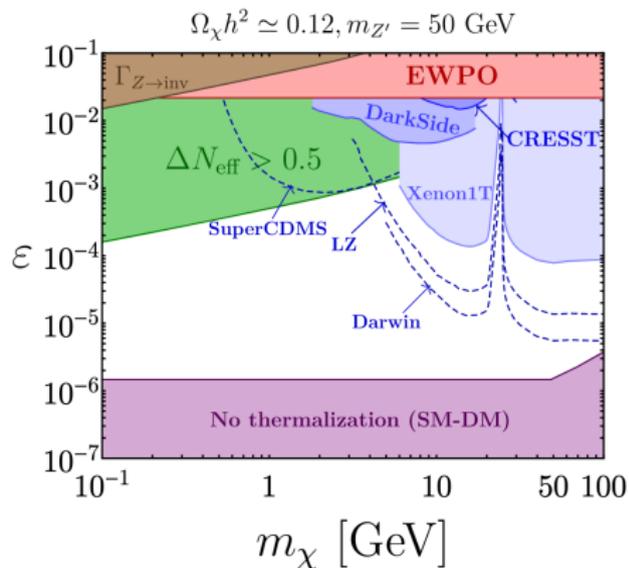
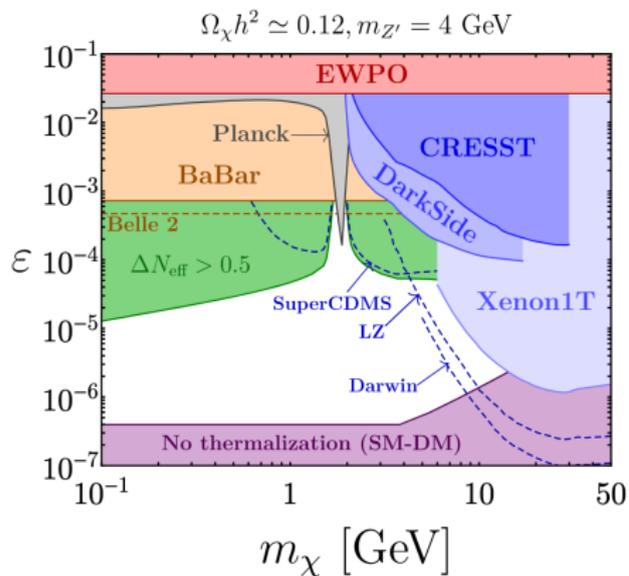


dominant annihilation channel $\bar{\chi}\chi \rightarrow \omega\omega$



$$\Delta N_{\text{eff}} = \left(\frac{43}{4}\right)^{4/3} \left(\frac{g_*^\omega(T_{\text{FO}})}{2}\right)^{4/3} \left(\frac{1}{g_*^{\text{SM}}(T_{\text{FO}})}\right)^{4/3}$$

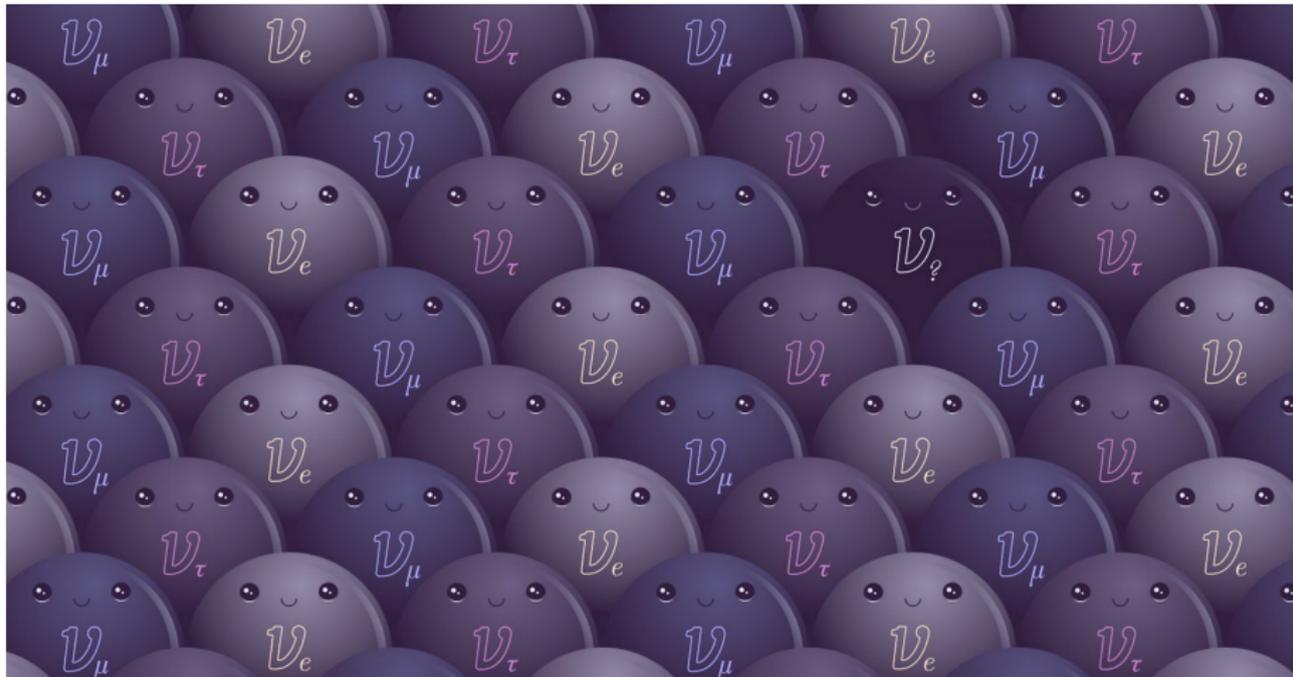




Summary and Conclusions

- ▶ constructed a hidden sector below the weak scale under which sterile neutrinos are charged
- ▶ need for additional particles leads to interesting phenomenology
- ▶ model presents three testable portals to the SM
- ▶ scalar and gauge boson with GeV masses
- ▶ DM candidate at GeV scale, massless fermion which contributes to N_{eff}

Thank you for your attention!



[all artwork from symmetry mag]

Backup: Other seesaw mechanisms

- ▶ linear seesaw:

$$M = \begin{pmatrix} 0 & m_D & \epsilon \\ m_D^T & 0 & M_N \\ \epsilon & M_N^T & 0 \end{pmatrix}$$

$$m_\nu \sim \epsilon \frac{m_D}{M_N}$$

- ▶ inverse seesaw:

$$M = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R^T \\ 0 & M_R & \mu \end{pmatrix}$$

$$M_R \gg \mu$$

$$\rightarrow m_\nu \sim \mu \frac{m_D^2}{M_R^2}$$

$$m_{ij} = \frac{1}{4\pi^2} N_F \sum_{k=4}^5 \left[C_{ik} C_{jk} \frac{m_k^3}{m_Z^2} F(m_k^2, m_Z^2, m_h^2) + D_{ik} D_{jk} \frac{m_k^3}{m_{Z'}^2} F(m_k^2, m_{Z'}^2, m_\phi^2) \right]$$

$$C_{ik} \equiv \frac{g_{Z'}}{4c_W} \sum_{\alpha=e}^{\tau} U_{\alpha i}^* U_{\alpha k}, \quad D_{ik} \equiv \frac{g_{Z'}}{2} U_{R' i}^* U_{R' k}$$

gauge portal:

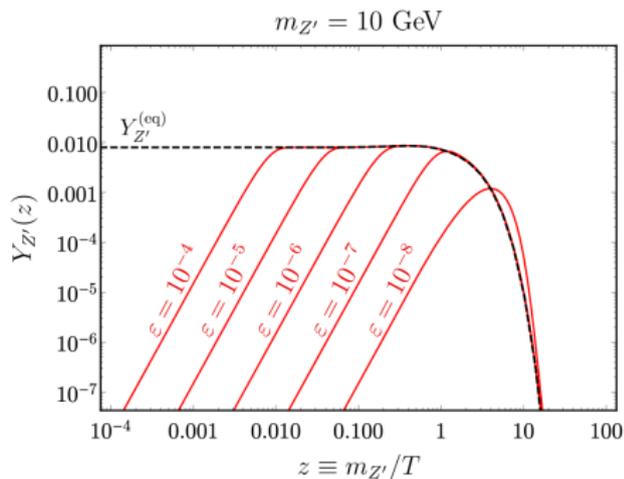
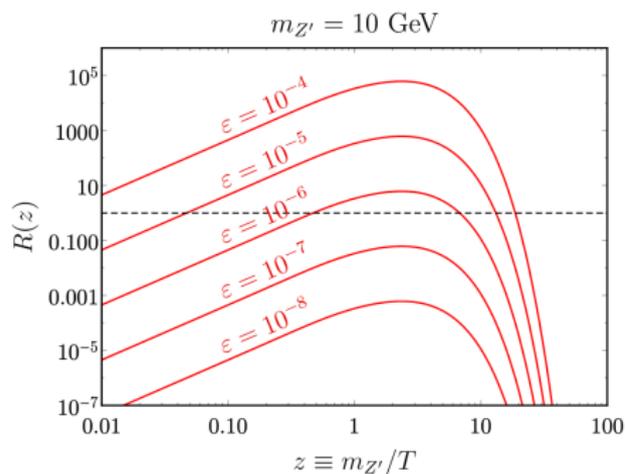
$$\tan(2\zeta) = \frac{m_Z^2 s_W \sin 2\xi}{m_{Z'}^2 - m_Z^2}$$

$$\mathcal{L} \supset e A_\mu J_{\text{EM}}^\mu + Z_{1\mu} \left[\frac{e}{s_W c_W} J_Z^\mu + g_{Z'} \varepsilon t_W J_{Z'}^\mu \right] + Z_{2\mu} \left[-e \varepsilon J_{\text{EM}}^\mu + g_{Z'} J_{Z'}^\mu \right]$$

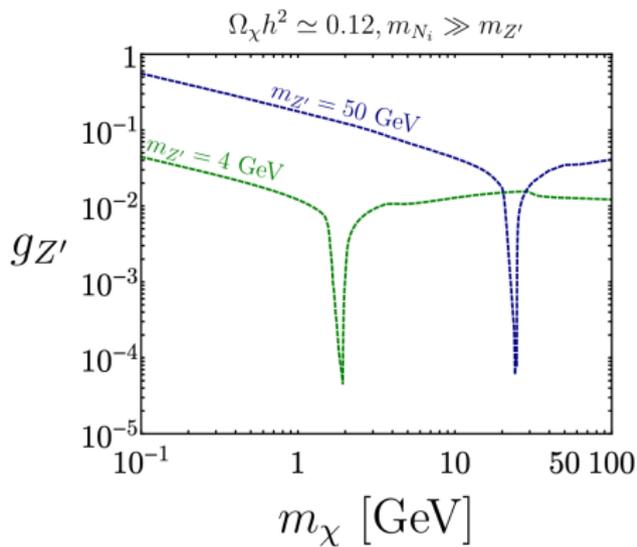
scalar portal:

$$\tan(2\alpha) = \frac{\lambda_{\phi h} v_h v_\phi}{\lambda_\phi v_\phi^2 - \lambda_h v_h^2}$$

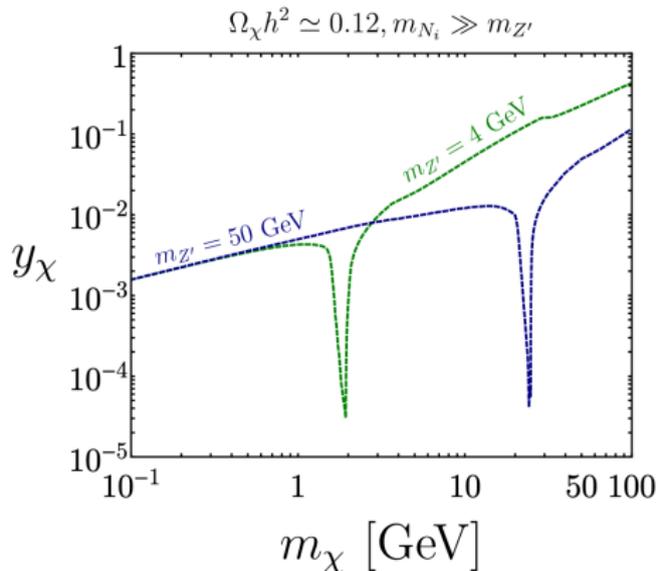
production of dark sector from inverse decays $\bar{\psi} + \psi \rightarrow Z'$



$g_{Z'} > y_\chi$: dominant $\bar{\chi}\chi \rightarrow \omega\omega$



$g_{Z'} < y_\chi$: dominant $\bar{\chi}\chi \rightarrow \phi\phi, N_{4,5}N_{4,5}$



(see also [Bertuzzo, Jana, Machado, Zukanovich Funchal '18])

